

Dark Matter Scattering in Neutron Stars

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DM Accretion on to Neutron Stars

For a concise recent review see Kouvaris (2013)

Mass accretion rate:

$$M_{\text{acc}} = 1.3 \times 10^{43} \left(\frac{\rho_{\text{dm}}}{0.3 \text{ GeV/cm}^3} \right) \left(\frac{t}{\text{Gyr}} \right) f \text{ GeV}$$

where $f = \text{Min} \left[1, \frac{\sigma}{10^{-45} \text{ cm}^2} \right]$

Thermalization:

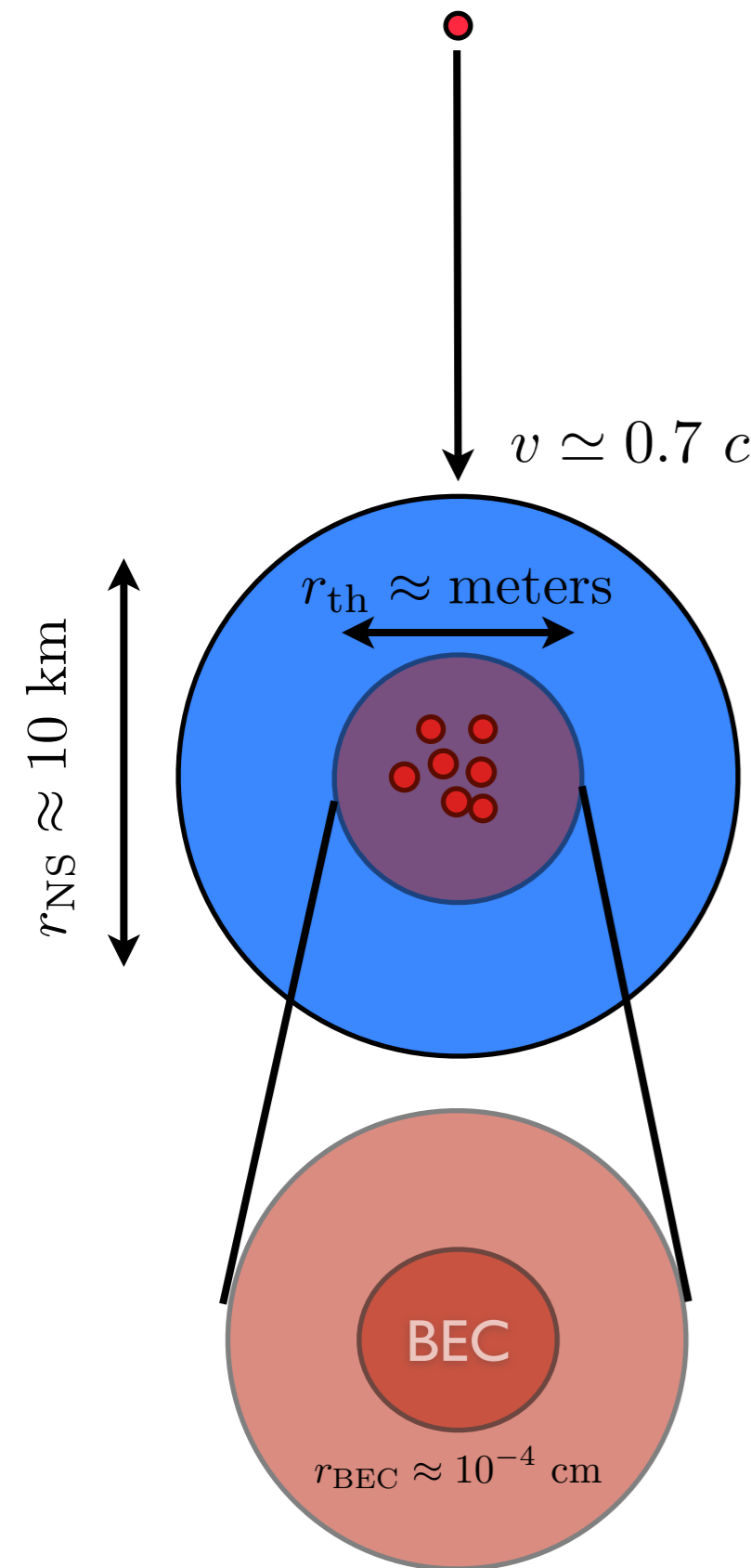
$$\frac{GM(r_{th})m_\chi}{r_{th}} \approx \frac{3}{2}T \Rightarrow r_{th} \approx 2.2 \text{ m} \left(\frac{T}{10^5 \text{ K}} \right)^{1/2} \left(\frac{\text{GeV}}{m_\chi} \right)^{1/2}$$

Self-Gravitation:

$$M_{\text{sg}} > \frac{4}{3}\pi\rho_c r_{\text{th}}^3 = 2.2 \times 10^{46} \text{ GeV} \left(\frac{m}{\text{GeV}} \right)^{-3/2}$$

Bose Einstein Condensation:

$$M_{\text{BEC}} > 8 \times 10^{27} \left(\frac{\text{GeV}}{m} \right)^{1.5} \text{ GeV}$$



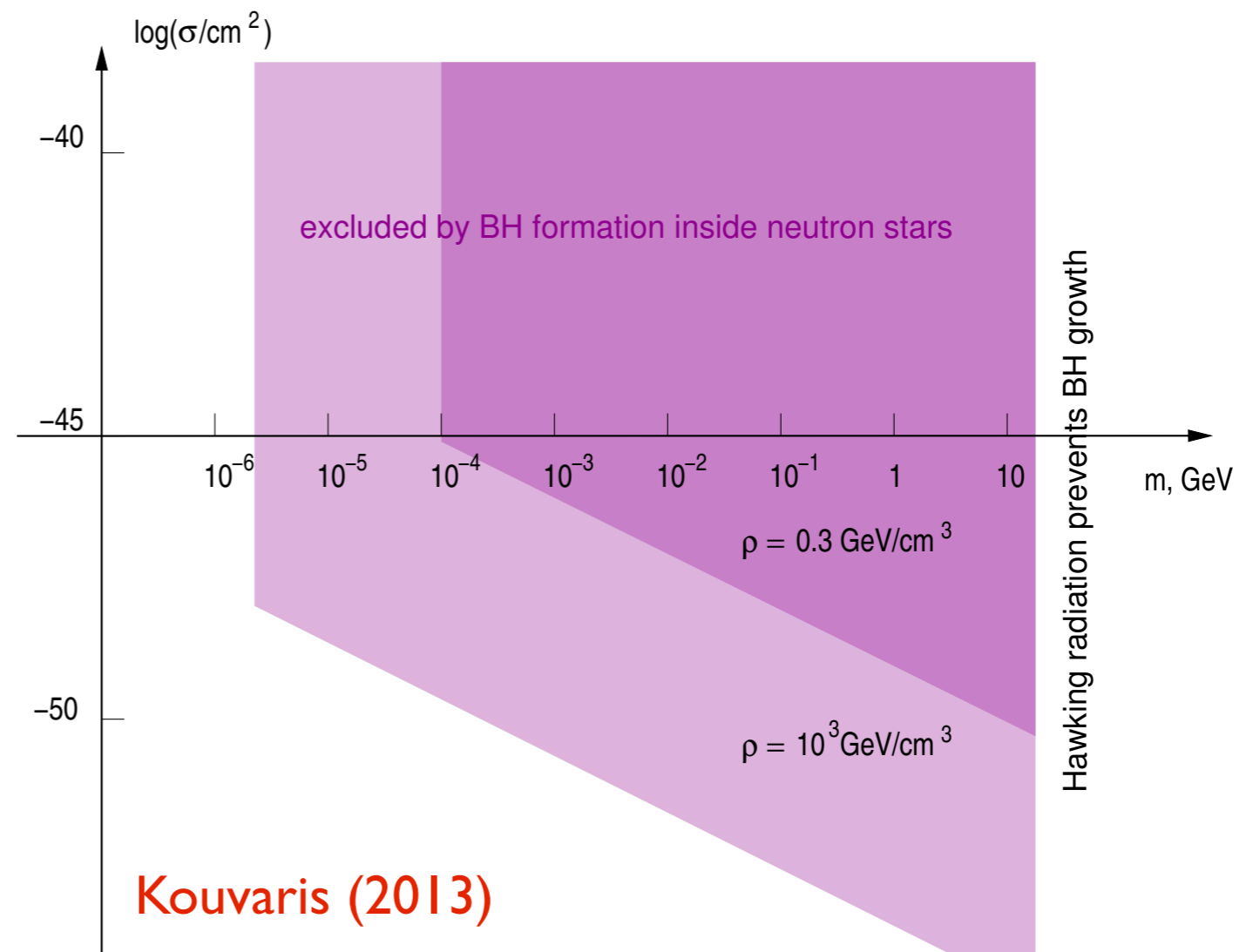
Black-hole Formation

Idea: Asymmetric bosonic dark matter can induce the collapse of the NS to a black hole. Goldman & Nussinov (1989)

This idea has been explored in more detail by:

- Kouvaris and Tinyakov (2011)
- McDermott, Yu and Zurek (2012)
- Kouvaris (2012) & (2013)
- Guver, Erkoca, Reno, Sarcevic (2012)
- Fan, Yang, Chang (2012)
- Bell, Melatos and Petraki (2013)
- Jamison (2013)

Existence of old neutron stars with estimated ages $\sim 10^{10}$ years provide strong constraints on asymmetric DM.



DM Scattering in the Neutron Star Core

Initial scattering is hard. Typical initial DM energy and momentum are large.

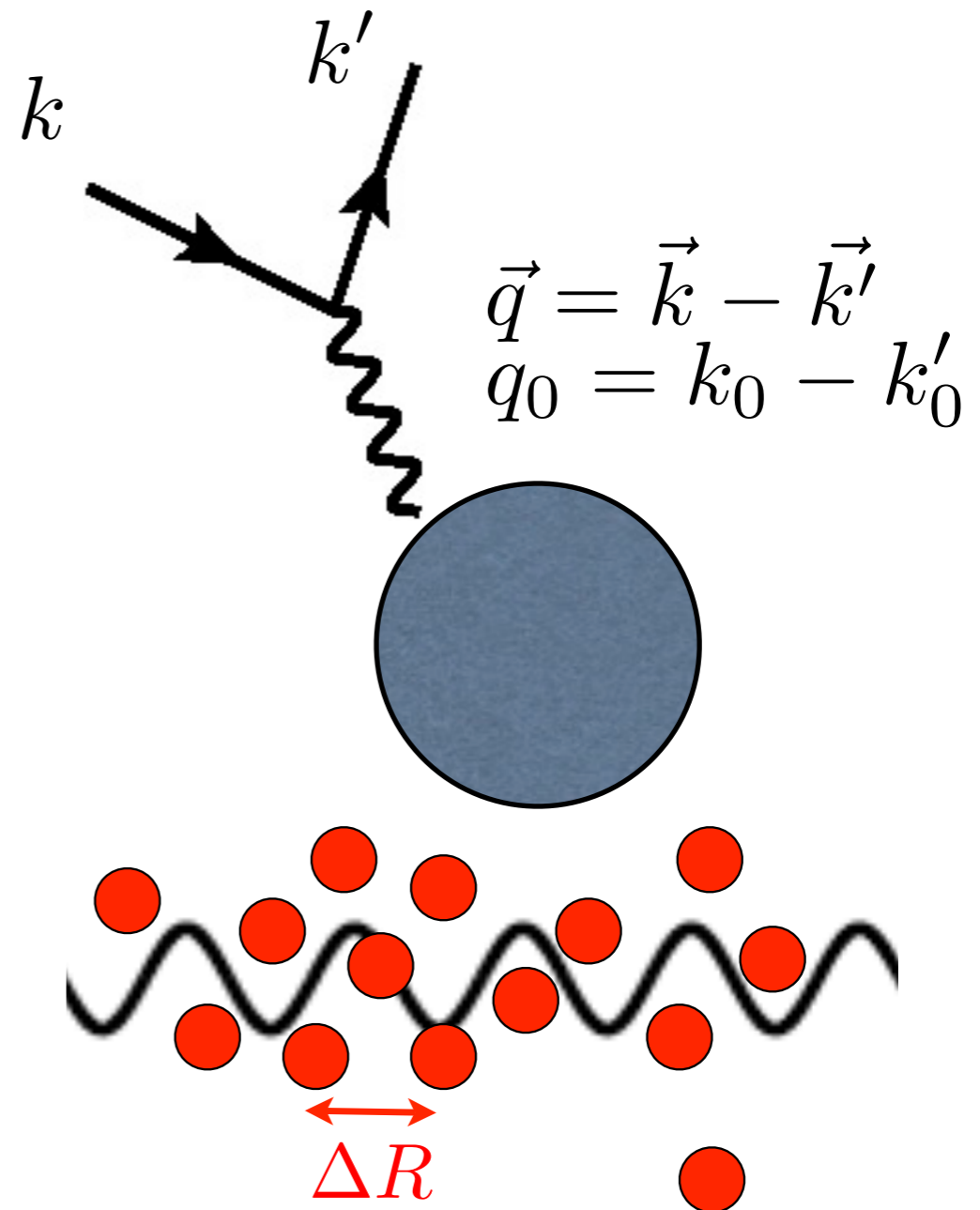
$$p_{\text{initial}} \sim m$$

$$E_{\text{initial}} \sim 1.4 m$$

As the DM loses energy it becomes increasingly soft. Typical energy and momentum transfer become comparable or smaller than characteristic scales in dense matter.

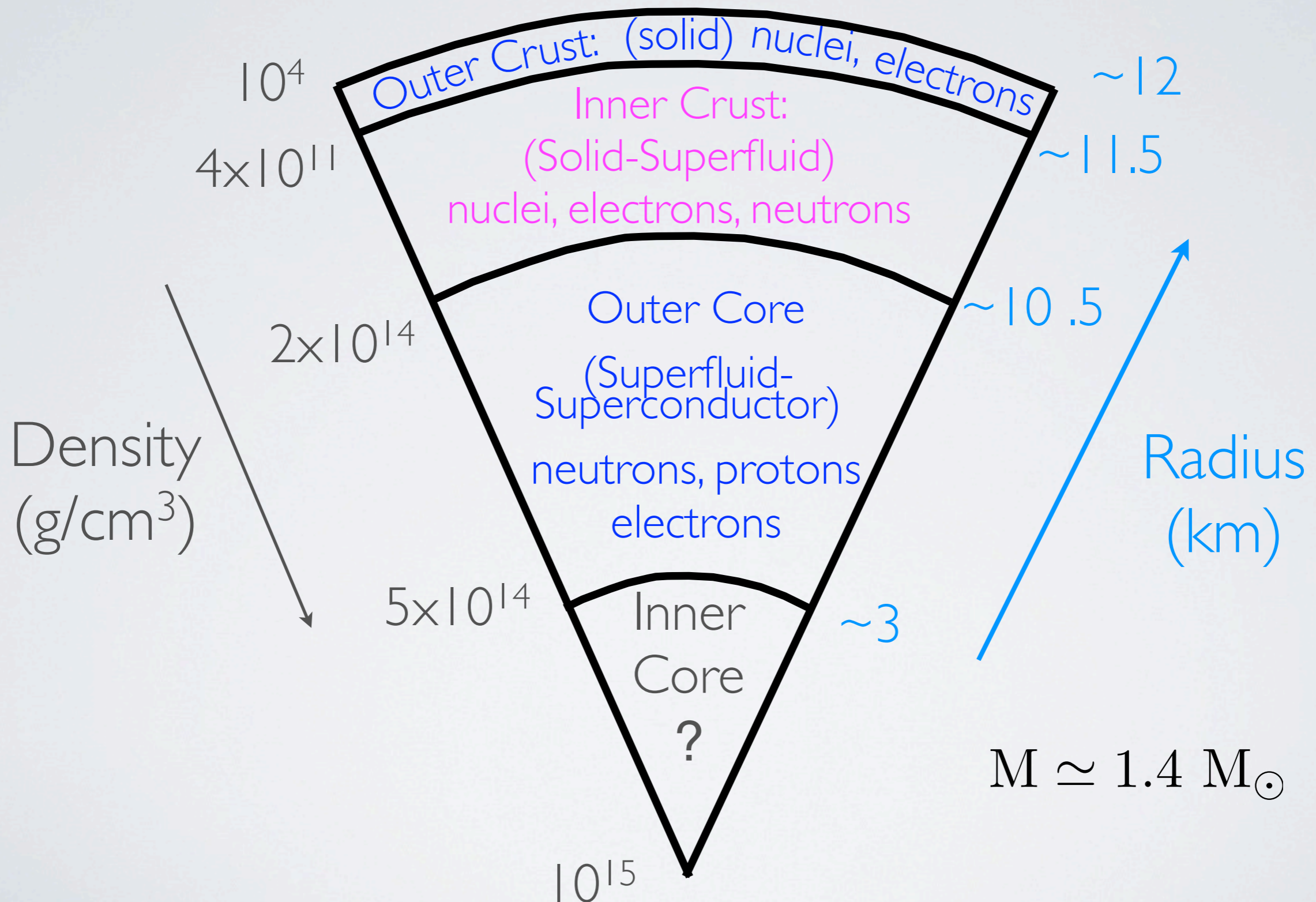
DM scatters off many-particles in the medium.

Interference between scattering off different target particles is important.



Theorists View of the Neutron Stars Interior

Cold and Complex



Correlations in Dense Matter and DM scattering

- Fermi Statistics (Pauli Blocking)
- Screening and Fermi Liquid Effects
- Multiple scattering suppression (Landau- Pomeranchuk-Migdal effects)
- Cooper Pairing and superfluid suppression.

Using a specific model of Asymmetric DM we study a few of these effects:

Bertoni, Nelson, Reddy (2013) in prep.

Complex scalar dark matter (Eg. mixed sneutrinos) :

$$\mathcal{L}_{int} = \tilde{G} \ell_{\mu} (j_V^{\mu} + \alpha j_A^{\mu})$$

$$\ell_{\mu} = \partial_{\mu} \chi^{\dagger} \chi - \chi^{\dagger} \partial_{\mu} \chi$$

Current associated with scalar DM

Vector and axial currents associated with baryons or electrons or quarks.

$$j_V^{\mu} = \bar{\psi} \gamma^{\mu} \psi$$
$$j_A^{\mu} = \bar{\psi} \gamma^{\mu} \gamma_5 \psi$$

$$\tilde{G} = \frac{g_{\chi} g_{\psi}^V}{M_H^2}$$

Effective coupling at low energy.

M_H is the mass of a heavy mediator.

DM Scattering in Many-Body Theory

Adapting the framework from studies of neutrino scattering. Eg. Reddy, Prakash, Lattimer (1998)

DM scattering rate : $\Gamma = -2\tilde{G}^2 \frac{1}{1 - e^{-q_0/T}} \int \frac{d^3k'}{(2\pi)^3} \frac{\text{Im}[\mathcal{L}^{\mu\nu}\Pi_{\mu\nu}^R]}{2E_k^\chi 2E_{k'}^\chi}$
(Optical Theorem)

$$\mathcal{L}_{\mu\nu} = (k + k')_\mu (k + k')_\nu \xrightarrow{\text{non-rel.}} 4m_\chi^2 \delta_{\mu 0} \delta_{\nu 0}$$

Correlation function in the medium:

$$\text{Im} [\Pi_{\mu\nu}^R] = \text{Im} \left[-i \tanh \left(\frac{q_0}{2T} \right) \times \int \frac{d^4p}{(2\pi)^4} \text{Tr} [G(p)(\gamma_\mu + \alpha\gamma_\mu\gamma_5)G(p+q)(\gamma_\nu + \alpha\gamma_\nu\gamma_5)] \right]$$

\uparrow
baryon or quark or electron Greens function
at finite temperature and density.

$$\xrightarrow[\text{non-interacting.}]{\text{non-rel.}} S(q_0, q) = \int \frac{d^3p}{(2\pi)^3} \int \frac{d^3p'}{(2\pi)^3} (2\pi)^4 \delta^4(p^\mu + k^\mu - p'^\mu - k'^\mu) n_F(E_p^n) (1 - n_F(E_{p'}^n))$$

dynamic structure factor for density fluctuations

DM Scattering in Degenerate Neutron Matter

Neglecting neutron-neutron interactions, but including Pauli blocking and kinematic constraints the scattering rate is :

$$\Gamma \approx 2\tilde{G}^2 \int \frac{d^3 k'}{(2\pi)^3} S(q_0, q) \quad \text{where} \quad S(q_0, q) \approx \frac{m_n^2 T}{2\pi q} \left(\frac{z}{1 - e^{-z}} \right) \Theta(qv_F - |q_0|)$$

$$\text{and} \quad z = \frac{q_0}{T}, \quad v_F = \frac{k_{Fn}}{m_n}$$

$$\tau \approx 3750 \text{ yrs} \frac{\gamma}{(1 + \gamma)^2} \left(\frac{2 \times 10^{-45} \text{ cm}^2}{\sigma} \right) \left(\frac{10^5 \text{ K}}{T} \right)^2$$

Thermalization time:

$$\text{where} \quad \sigma_{DM-f} = \frac{\tilde{G}^2}{\pi} \frac{m_f^2 m_\chi^2}{(m_f + m_\chi)^2} \quad \text{and} \quad \gamma = \frac{m_\chi}{m_n}$$

Earlier estimates found that :

Goldman & Nussinov (1989)
Kouvaris and Tinyakov (2011)
McDermott, Yu and Zurek (2012)

$$\tau \simeq 10^{-5} \text{ yrs} \left(\frac{m}{\text{GeV}} \right)^2 \left(\frac{2 \times 10^{-45} \text{ cm}^2}{\sigma} \right) \left(\frac{10^5 \text{ K}}{T} \right)$$

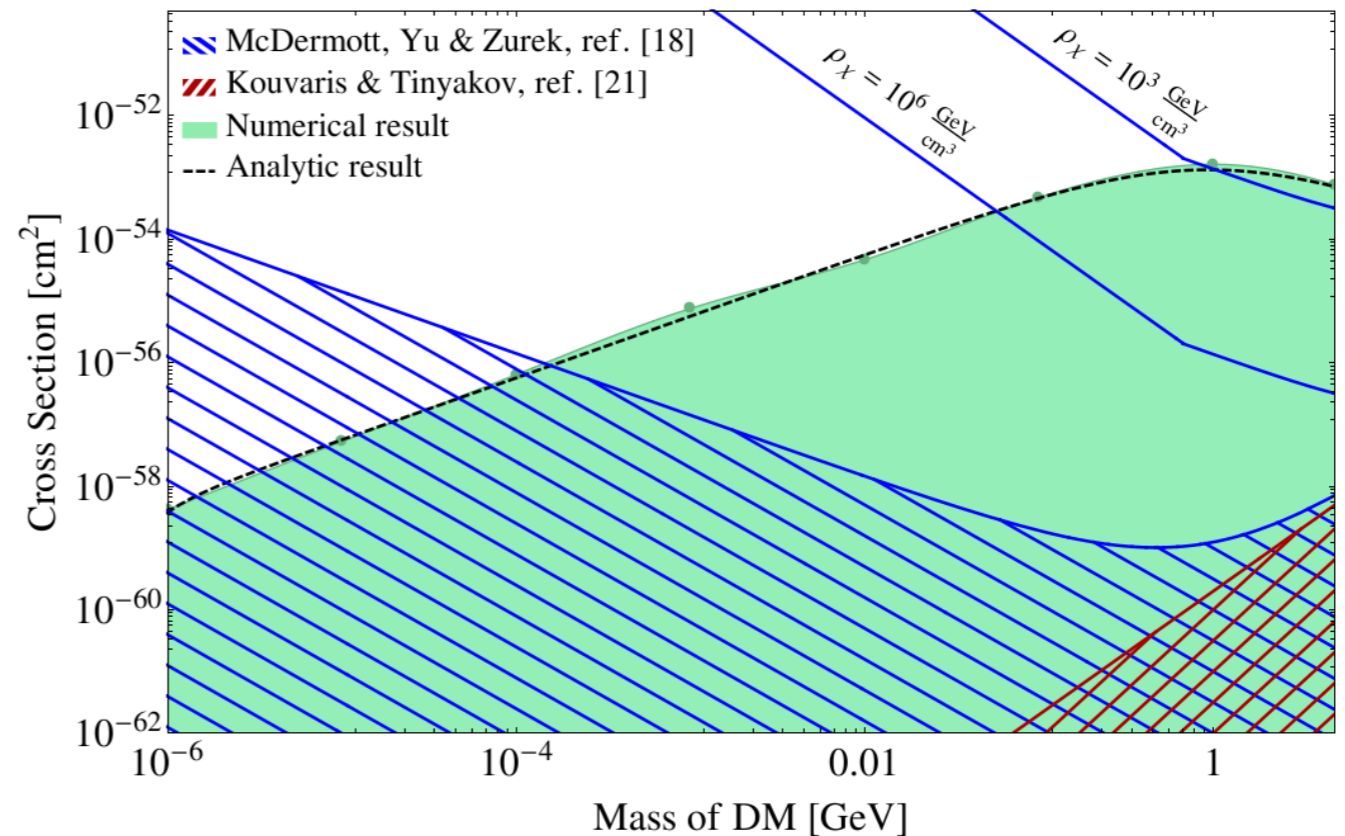
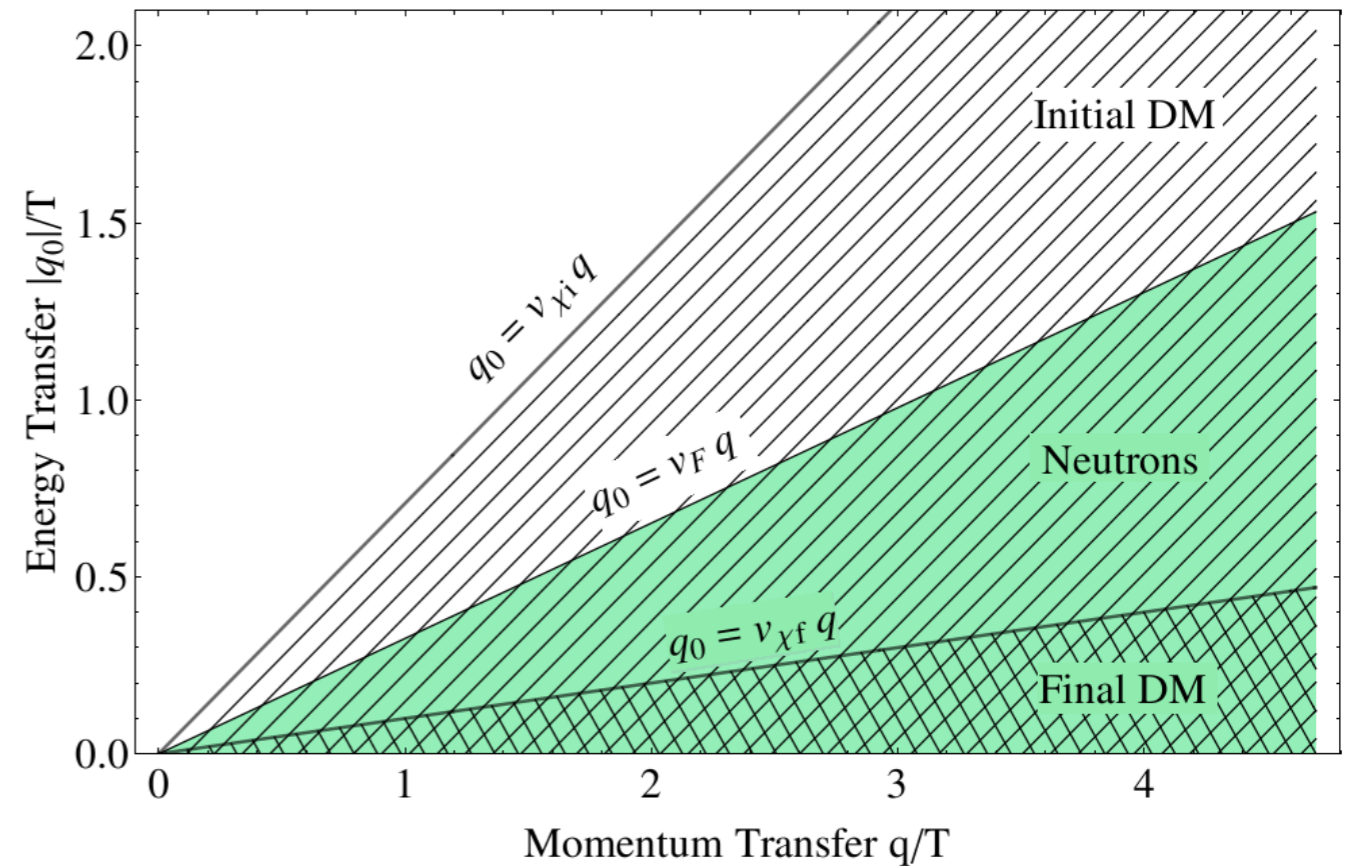
Kinematic Constraints

Kinematics is quite restricted when DM velocity becomes small.

When $v_\chi \ll v_F$

only a small fraction of neutrons respond.

Still, thermalization occurs in the less than 10^{10} years even for relatively small cross-sections $> 10^{-52} \text{ cm}^2$.



Nucleons are Frozen

Theory predicts that neutrons will form spin-triplet Cooper pairs and protons form spin-singlet pairs

$$\Delta \simeq 0.1 - 1 \text{ MeV}$$

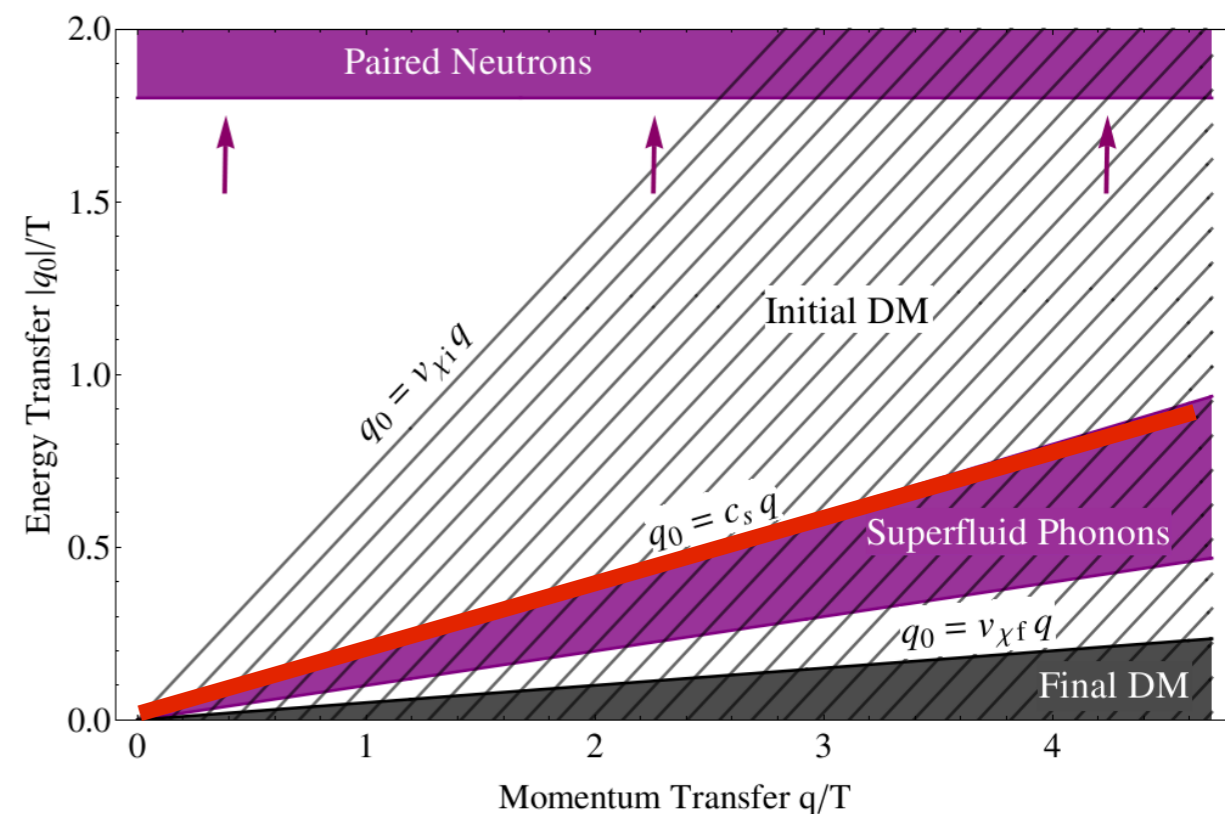
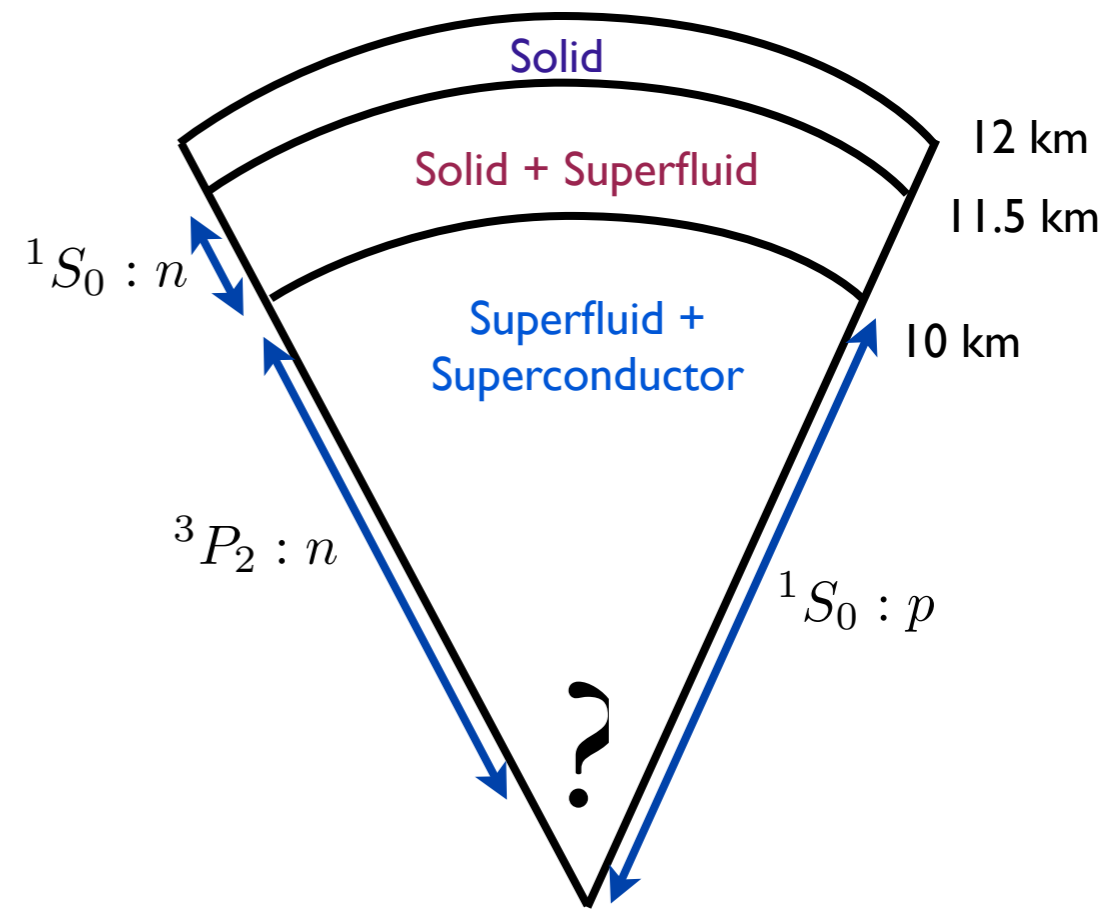
Nucleons cannot be excited below the gap.

Low-energy nucleon response is solely due to the excitation of Goldstone bosons (superfluid phonons)

$$S(q_0, q) = \frac{\pi n_n}{2m_n c_s^2} q_0 \delta(q_0 - c_s q)$$

DM-nucleon scattering is negligible when

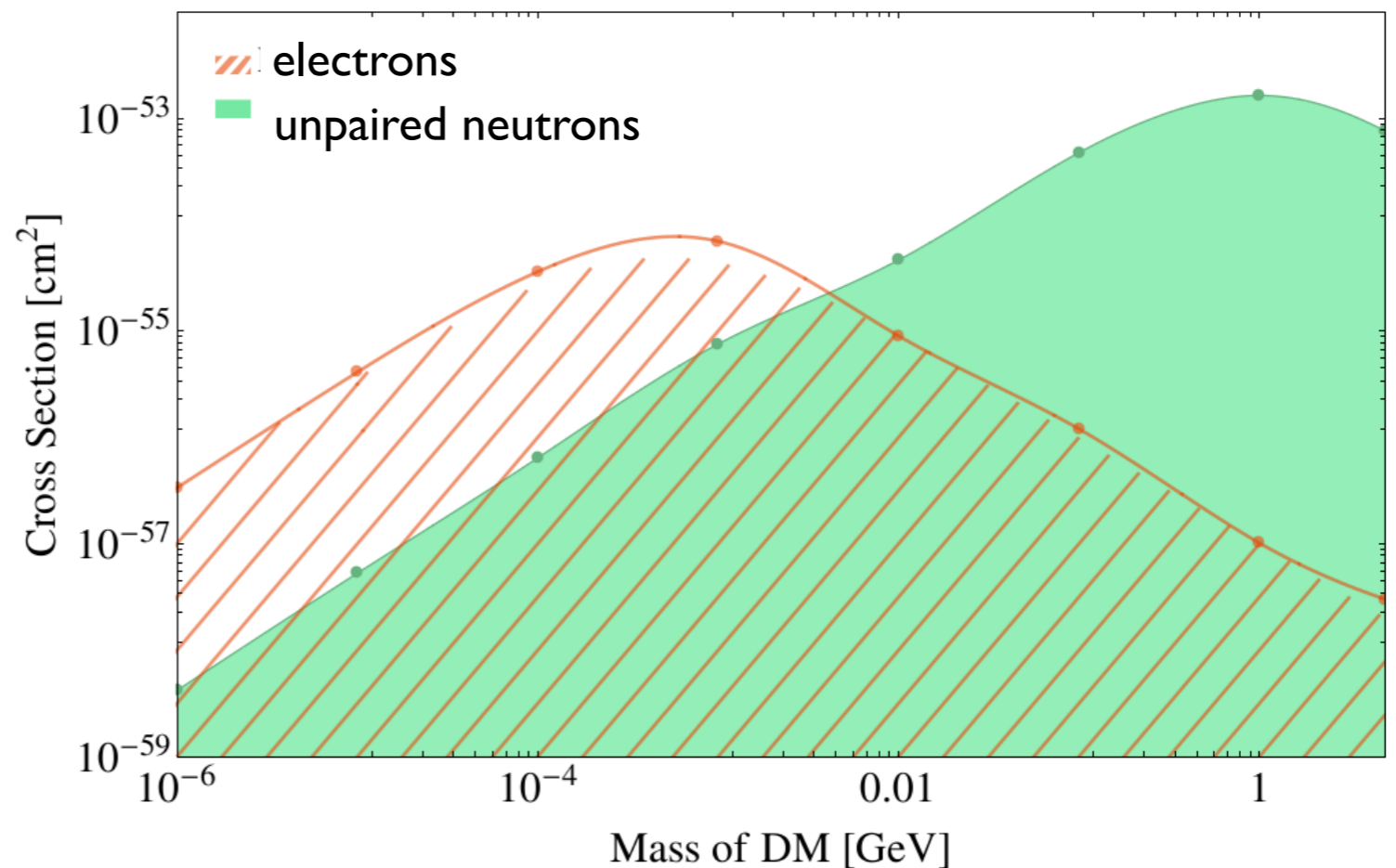
$$v_\chi < c_s$$



DM - Electron Scattering

All dense nuclear phases contain electrons.

DM-electron scattering dominates.



- Thermalization time will be short compared to the age of the neutron star in all phases of dense nuclear matter.
- Robust because of the existence of a normal dense electron gas.

Superfluid Phases Without Electrons

There are two well motivated phases of quark matter at high density that are devoid of electrons

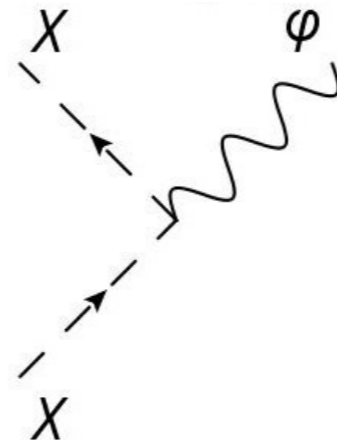
- Color Flavor Locked (CFL) Quark Matter
- CFL + Kaon condensed matter

In these phases the only relevant low-energy degrees of freedom are the Goldstone bosons (phonons) - quarks are all gapped.

Two phonon process is too weak.

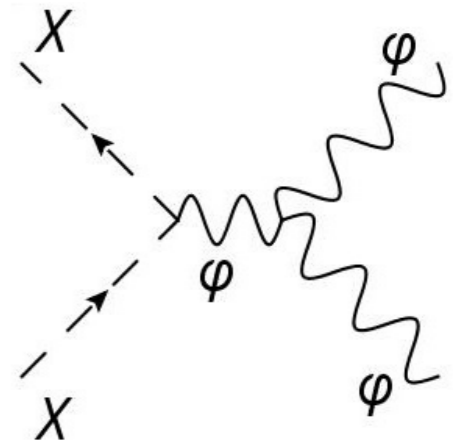
$$\Gamma(p) \approx \frac{c_3^2 (\alpha/2)^6}{8\pi^4 c_h^4} \tilde{G}^2 T^5 \frac{T^2}{f_h^2} \frac{T^2}{m_\chi p}$$

one-phonon



$$v_\chi > c_s$$

two-phonon



$$v_\chi < c_s$$

Thermalization in $< 10^{10}$ yrs is not possible in these exotic phases.

Conclusions



DM scattering in neutron stars is complicated by correlations and superfluidity in the dense medium.



An improved treatment of DM - scattering in dense matter is needed to explore the role of DM in neutron star phenomenology.



The discovery of Asymmetric bosonic DM in the laboratory would favor the existence of an exotic phase in the neutron star core.